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A BUNCHING SCHEME FOR FEL APPLICATIONS AT CEBAF*

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Abstract

A project using the CEBAF superconducting RF linac to drive both IR and UV FEL's is being considered. Although the linac, primarily designed for nuclear physics, need not be modified, a high intensity beam source must be added. The source will provide up to 60 A peak and 0.9 mA average current within a 15 mm mrad normalized emittance. Such currents, together with the small energy spread expected from CEBAF, yield a high optical gain and 1 kW of average optical power from each FEL. A bunching scheme from the source to the injector exit is presented with PARMELA calculations of the space charge dominated dynamics.

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Introduction

A proposal to use the CEBAF nuclear physics facility to drive two versatile high power FEL's is being developed [1]. The first proposed FEL would be driven by the 45 MeV CEBAF injector, producing output in the infrared, from 4.5 to 20 μm. The second FEL would be powered by the 400 MeV CEBAF North Linac to produce light output in the deep ultraviolet regime around 200 nm. A key difference between the beam requirements for an FEL driver and for nuclear physics is that the FEL requires high peak intensity beam. Therefore, the CEBAF FEL's will utilize a high brightness photoemission gun with compression of its output beam to about 60 A peak current within a 15 mm mrad normalized emittance.

The photoemission gun is discussed in detail by C. Sinclair [2]. The gun will deliver 100 psec long, 500 keV bunches of 120 pC charge at a repetition rate of 7.485 MHz. The beam must be bunched and preaccelerated before full acceleration in the CEBAF injector. We propose a scheme which longitudinally compresses the 100 psec bunches down to 2 psec, while accelerating them up to 10 MeV. The scheme has been developed using PARMELA [3] for detailed calculations of the space charge dominated dynamics. The method produces 2 psec bunches with 2×10^{-3} rms momentum spread at 45 MeV and no significant emittance dilution from a nominal 10 mm mrad normalized emittance. In the following sections we describe the bunching scheme, and present and discuss calculations of transverse and longitudinal dynamics.

Description of the Bunching Section

Figure 1 shows a schematic of the bunching section, from the photoemission gun to the first 20 MeV accelerating module of the CEBAF injector. At the gun exit, the beam drifts for 60 cm, and passes through a 10 cm long solenoid before entering a room temperature 2-cell fundamental frequency prebuncher. The latter is about 20 cm long and its last cell is surrounded by a solenoid to focus the beam into a cryounit which follows immediately downstream from the prebuncher. This cryounit is 252 cm long and contains two of the CEBAF 5-cell superconducting cavities. At the cryounit exit, the beam is focussed through a solenoid or a triplet of quadrupoles and drifts for 200 cm. This long drift is needed before the two cryomodules of the CEBAF injector for vacuum pumps, beam diagnostics, steerers and the injection of the nuclear physics beam. Each of the cryomodules contains 8 five-cell 1497 MHz CEBAF cavities and provides 20 MeV acceleration.

Longitudinal Compression of the Beam

Figures 2 and 3 show the changes in bunch length and energy spread along the FEL injector line following the photoemission gun, as calculated in a PARMELA simulation. At the gun exit the beam has a mean energy of 0.5 MeV with an energy spread of 1 keV and a bunch length of 100 psec. Between the gun and the prebuncher, the beam debunches slightly under space charge forces.

At the prebuncher the beam receives a bunching voltage, obtaining a bunching energy tilt of 100 keV over the 100 psec bunch length. The prebuncher is a 1497 MHz two cell room temperature cavity of the Los Alamos side-coupled type. The required prebunching gradients are 0.7 to 1.3 MeV/m, similar to the CEBAF nuclear physics injector capture section. In operation, the prebuncher will be used for the fine-tuning of beam parameters, with the cryounit and the cryomodules set to relatively fixed parameters.

The prebuncher is followed closely by the FEL injection cryounit, and the bunch is compressed by a factor of 5 during transport into the cryounit. The cryounit contains two superconducting 5-cell 1497 MHz cavities with an active 5-cell length of 50 cm. The cavities can be powered independently in amplitude and phase, and are operated at gradients up to 10 MV/m. This is twice the initial design specification of 5 MV/m, but gradients of 10 MV/m have been achieved in system tests [4]. The phase and gradient flexibility permits simultaneous bunching and acceleration of the beam within the length of the cryounit. Shorter bunches with less space charge degradation of emittances are therefore attainable, as compared with the low energy prebuncher-only system. In this example, the first cavity is set on the 23° off crest bunching phase, while the second cavity is on crest (0°), and both are powered at 10 MV/m. At the end of the cryounit we obtain a 10 MeV beam with 120 pC within 2 psec, with an energy spread of 100 keV. The 10 MeV energy is twice the nuclear physics beam energy at this point. The energy offset is used to combine the beams in a chicane before the first cryomodule. The higher energy also permits better control of space charge effects.

Along the 250 cm separation between the cryounit and the first CEBAF cryomodule, space charge forces increase the energy spread to 200 keV but do not increase the bunch length. In order to counter the space charge energy tilt, the FEL beam will be driven off crest by 25° by both cryomodules, to reduce the energy spread to 100 keV. Figure 4 shows results of a PARMELA simulation, showing the longitudinal distribution of the beam at the end of the last cryomodule with energy and phase projections. The results show 120 pC of beam within 2 psec, obtaining the 60 A specification needed for the CEBAF FEL proposal.

Transverse Focussing of the Beam

A typical result of a PARMELA transverse beam dynamics calculation is shown in Figure 5. In the transverse optics of the bunching section, the main concern is to keep the beam size under control through the 252 cm long cryounit. Along this length, no focussing can be applied and space charge forces become stronger because the beam is longitudinally compressed and not fully accelerated. PARMELA calculations have shown that for the beam to exit from the cryounit with a radius not exceeding 7.5 mm, the beam ellipse in transverse phase space must be upright or converging at the entrance of the first superconducting cavity. To obtain these conditions, two solenoidal lenses, which image the gun exit in the cavity, are used. The first solenoid with a maximum field of 270 gauss stops the transverse expansion of the beam such that the transverse beam ellipse is upright through the prebuncher. The second solenoid is located as close as possible to the cryounit, obtaining a beam waist at the entrance of the first cavity or farther downstream. In our calculations the second solenoid surrounds the second cell of the prebuncher with a peak field of 245 gauss. The optimum drift length between the gun and the first lens may vary depending on the beam spot size at the anode aperture, assuming the delivered emittance is fixed. With spot radii from 3 to 6 mm at the anode aperture, calculations have shown that the beam can travel through the cryounit with a transverse radius of no more than 1 cm. This size is well within the cryounit physical aperture of 3.5 cm.

At the cryounit exit a 30 cm long, 450 gauss solenoid suffices to focus the 10 MeV beam through the two cryomodules to the end of the injector. Using a triplet of quadrupoles instead of this axial lens is also being considered. Quadrupoles would occupy about the same longitudinal space and provide the same focussing strength as the solenoid.

Thus, the transverse focussing in the proposed scheme, which includes two solenoids near the prebuncher cavity and another solenoid or quadrupole triplet following the cryounit, are sufficient to keep the beam confined within a 1 cm radius, with little phase space dilution from space charge, as calculated with PARMELA simulations.

PARMELA Calculations

We used PARMELA to compute the dynamics of 500 particles representing a total charge of 160 pC, generated from the set of parameters which characterize the beam at the gun anode. At the input, the particles are uniformly distributed in an upright 4-D ellipsoid of transverse phase space, with a 10 mm mrad normalized emittance and a radius of 5 mm. The particle distribution is gaussian in the longitudinal phase space ellipse, where the 4σ-widths of the momentum and phase spreads are 1 keV and 54° (100 psec). Figure 4 shows the resulting longitudinal phase space at the injector exit and the corresponding phase and energy spectra.

The shape of the bunch in longitudinal phase space shows low density tails produced by space charge forces. Collimation to remove these tails may be needed. In our calculations, the space charge mesh is resized twice as the bunch is being compressed, for accurate representation of the high density core of the beam ($\pm 1°$). Consequently, the tails are not included in the space charge calculation past the first superconducting cavity. Future calculations with a larger mesh version of PARMELA will correct this. However, the computation of the core dynamics shows a 60 A average current over 2 psec (1.1°) of the bunch length, and an energy spread smaller than 2×10^{-3}.

Figure 6 and 7 show the variations of the transverse and longitudinal emittances respectively, from the gun anode to the 45 MeV injector exit. The lower curve on the transverse emittance plot shows the result of switching off the space charge effects in our calculation without changes of the input. These three curves demonstrates the importance of cautiously designing the prebunching section from the gun to the cryounit, where most of the increase in emittances occurs. They also show the ability of superconducting CEBAF cavities to compress to high peak currents, with small transverse emittance growth: less than 12% with our design, and a longitudinal rms emittance of 90 keV deg including the bunch tails.

The beam dynamics in this front end contains several unique properties, which represent a new parameter regime for PARMELA and need further study. At the end of the cryounit the bunch length is much shorter than its transverse size: 0.6 mm long compared to 5 mm radius, the opposite of the usual situation. Also, with the high pulse compression, longitudinal space charge effects are important within the highly relativistic 5 to 10 MeV beam at the cryounit exit. In previous electron linacs, the $1/\gamma^3$-dependent space charge effects are negligible at these energies because of lower peak currents.

Discussion and Future Development

We have demonstrated a possible design for the front end of the CEBAF FEL which compresses beam from the photoemission gun to obtain 60 A peak current within 2 psec, within energy spread and emittance constraints. Future work will explore variations of this front end to find an optimal design. Also the adaptability must be studied, *i.e.*, error sensitivity and tunability of the front end design to varying beam conditions and requirements. The issue of a longitudinal emittance filter to dump bunch tails will be studied. An engineering design must be developed which may expose practical difficulties such as aperture, spacing, collimation and beam combination problems.

While 60 A current is more than adequate for the IR FEL, a higher current is desired for the UV FEL. In reference [1], a 120 A peak current for the UV FEL is proposed, obtained by magnetic compression at full energy. It would be preferable to obtain the additional compression within the front end transport, however our initial design efforts appear limited to peak currents of 60 A. Future studies will attempt to optimize the transport to increase compression, and to understand or overcome the limitations.

References

[1] G. R. Neil, *et al.*,"FEL Design Using the CEBAF Linac," these proceedings.

[2] C. Sinclair, "A 500 kV Photoemission Electron Gun for the CEBAF FEL," these proceedings.

[3] L. M. Young, "PARMELA," software Copyright 1991, unpublished.

[4] Peter Kneisel, *et al.*, Performance of superconducting cavities for CEBAF, TN #91-032.

Figure Captions

Figure 1. Schematic of the bunching section, from the photogun to the entrance of the first 20 MeV cryomodule of the CEBAF injector.

Figure 2. Particle phases relative to the reference orbit, plotted at various locations along the injector, showing the bunch length behavior.

Figure 3. Particle energies relative to the reference energy, plotted at various locations along the injector, showing the bunch momentum spread behavior.

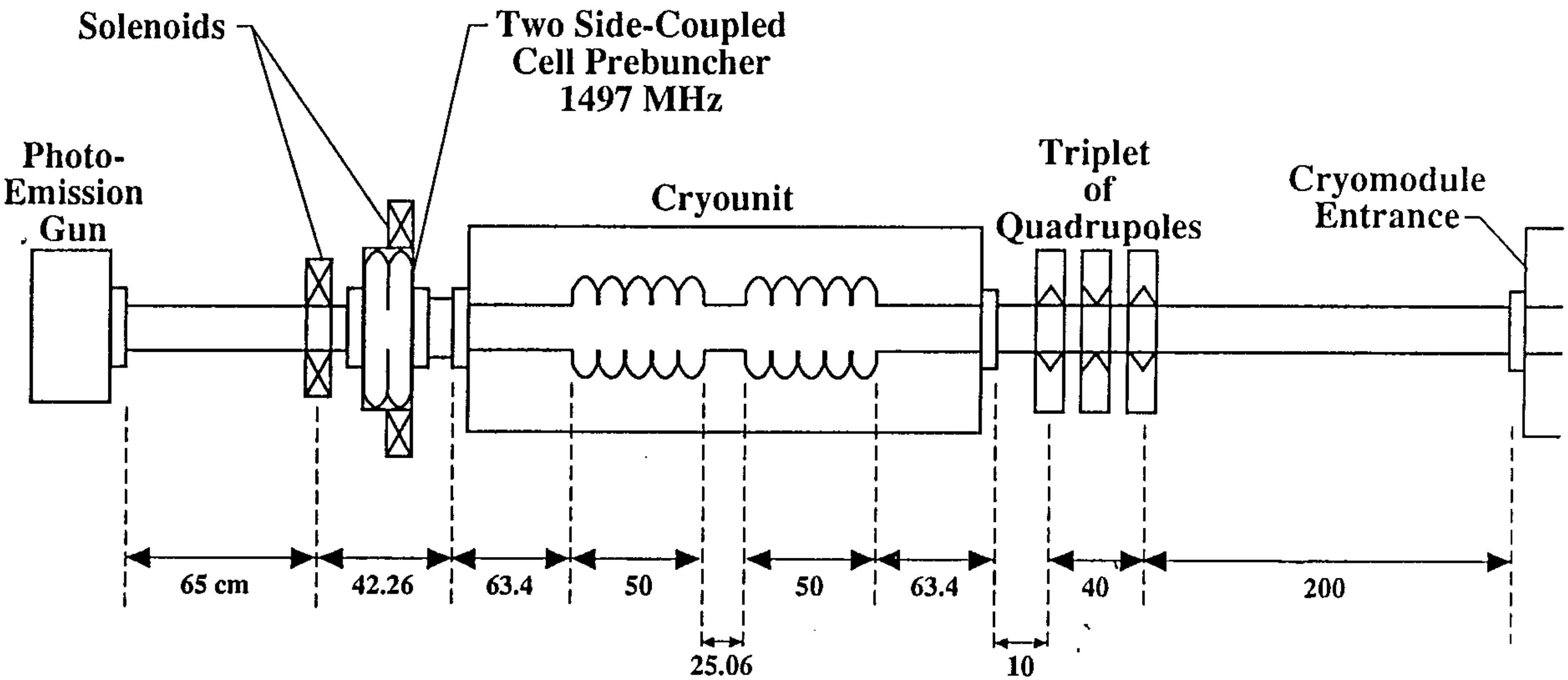
Figure 4. (a) output longitudinal phase space of the CEBAF FEL injector. (b) 1497 MHz phase spectrum. (c) 45 MeV energy spread spectrum.

Figure 5. Transverse size of the beam given at various locations along the injector.

Figure 6. Transverse rms normalized emittance vs. longitudinal location in the CEBAF FEL injector.

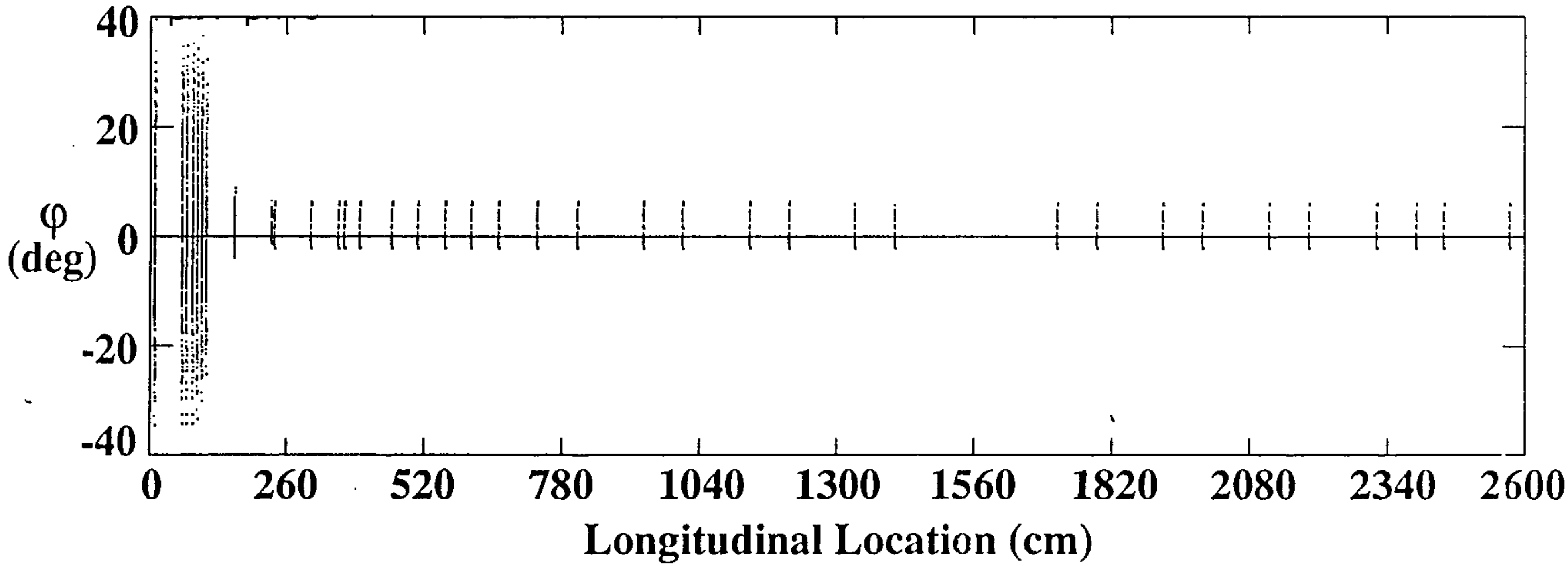
Figure 7. Longitudinal rms emittance vs. longitudinal location in the CEBAF FEL injector.

Figure 1



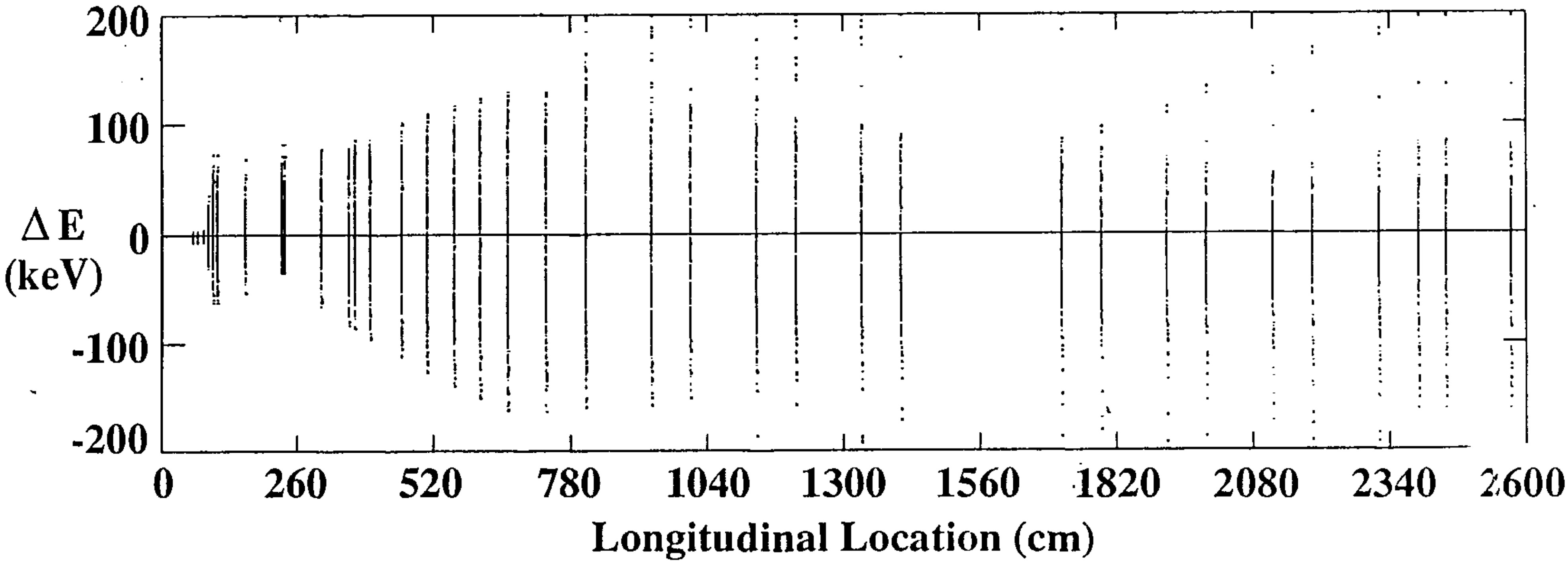
Solenoids
Two Side-Coupled Cell Prebuncher 1497 MHz
Photo-Emission Gun
Cryounit
Triplet of Quadrupoles
Cryomodule Entrance
65 cm
42.26
63.4
50
50
63.4
40
200
25.06
10

Figure 2



40
20
0
-20
-40
φ (deg)
0
260
520
780
1040
1300
1560
1820
2080
2340
2600
Longitudinal Location (cm)

Figure 3



200
100
0
-100
-200
ΔE
(keV)
0
260
520
780
1040
1300
1560
1820
2080
2340
2600
Longitudinal Location (cm)

Figure 4a

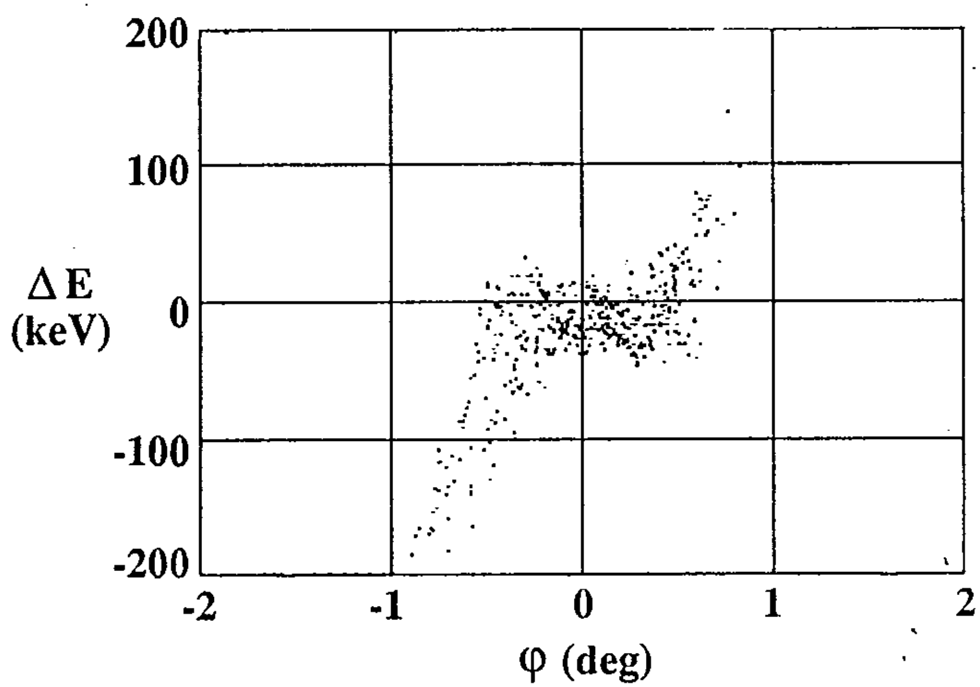


Figure 4b

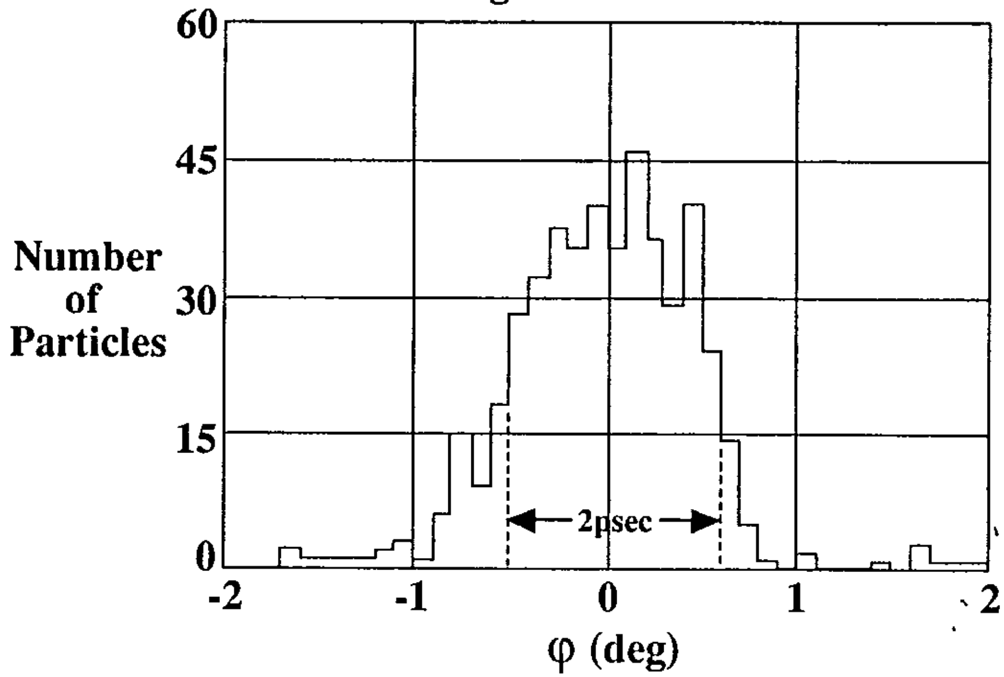


Figure 4c

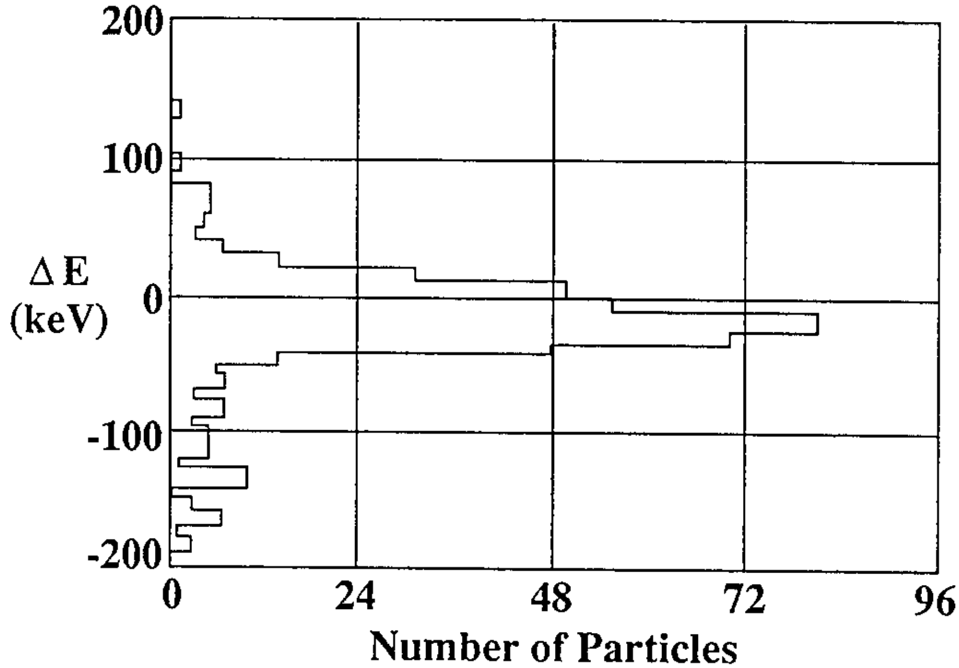


Figure 5

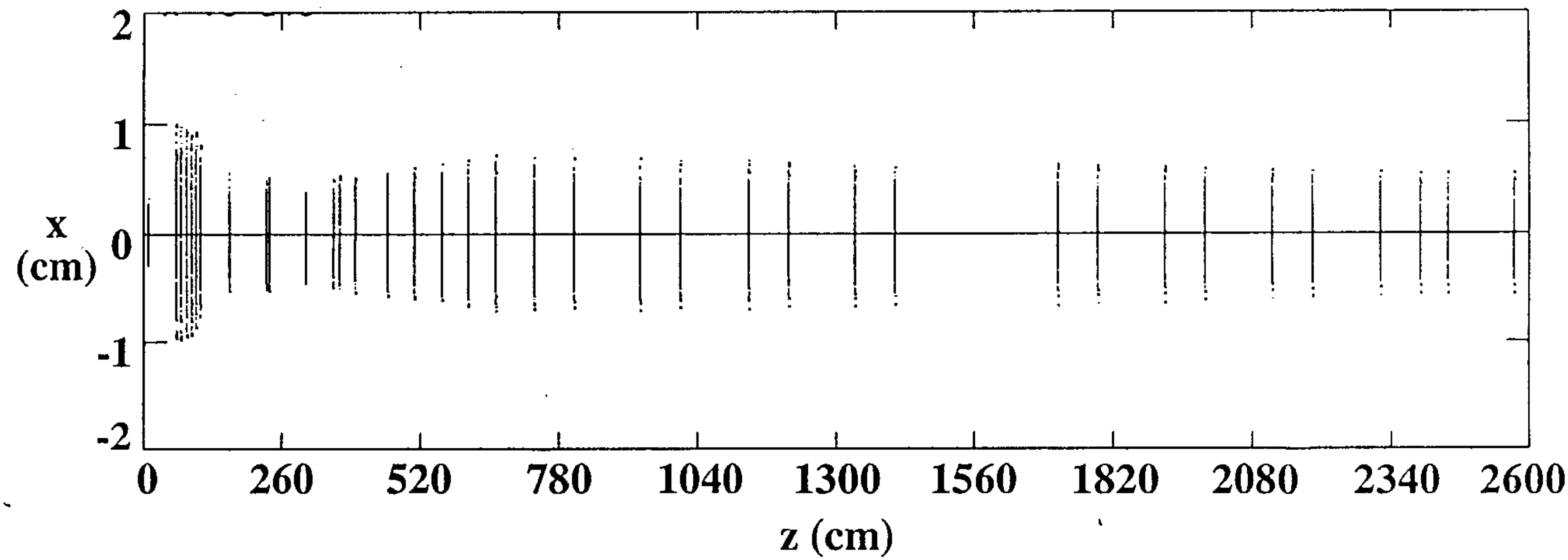
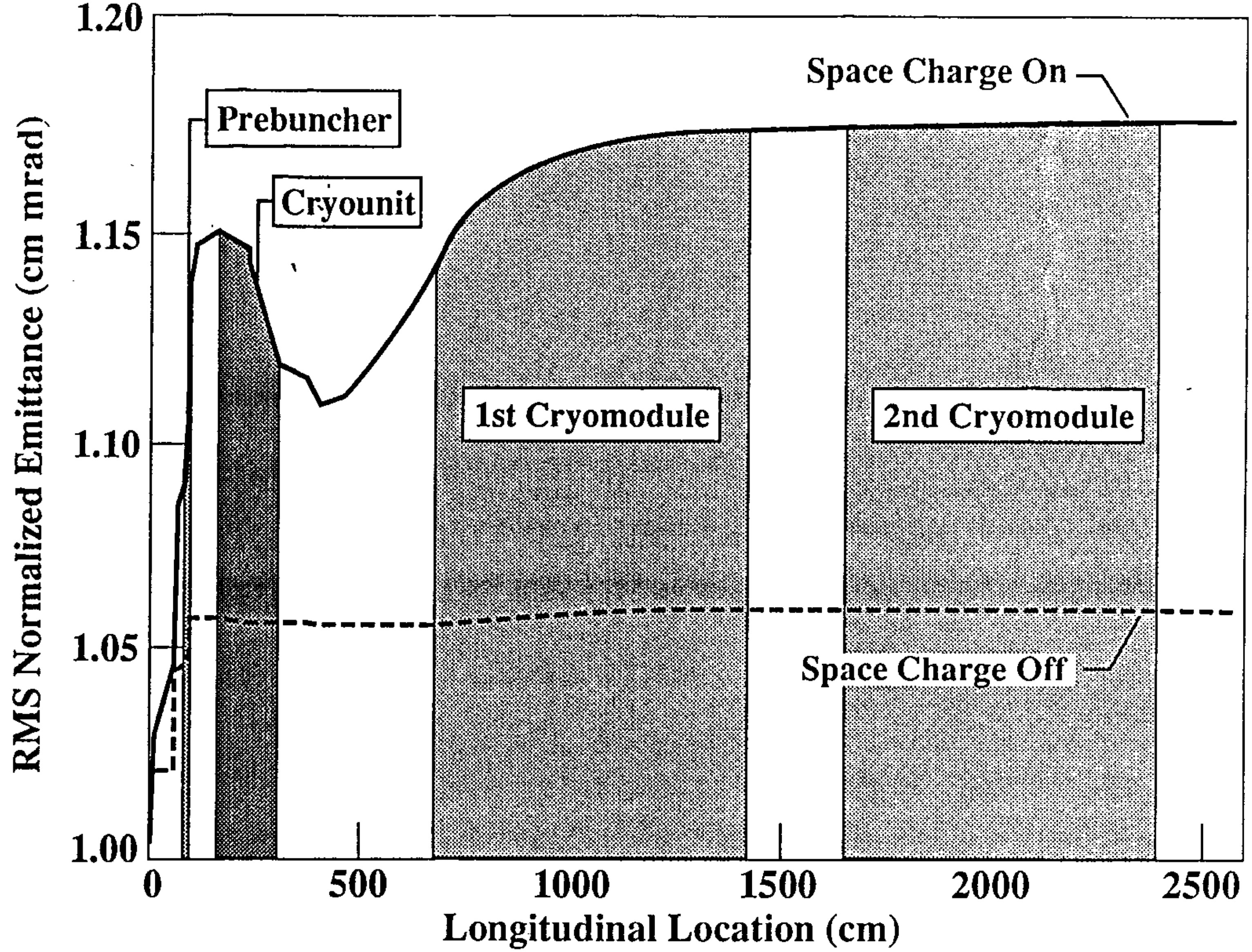
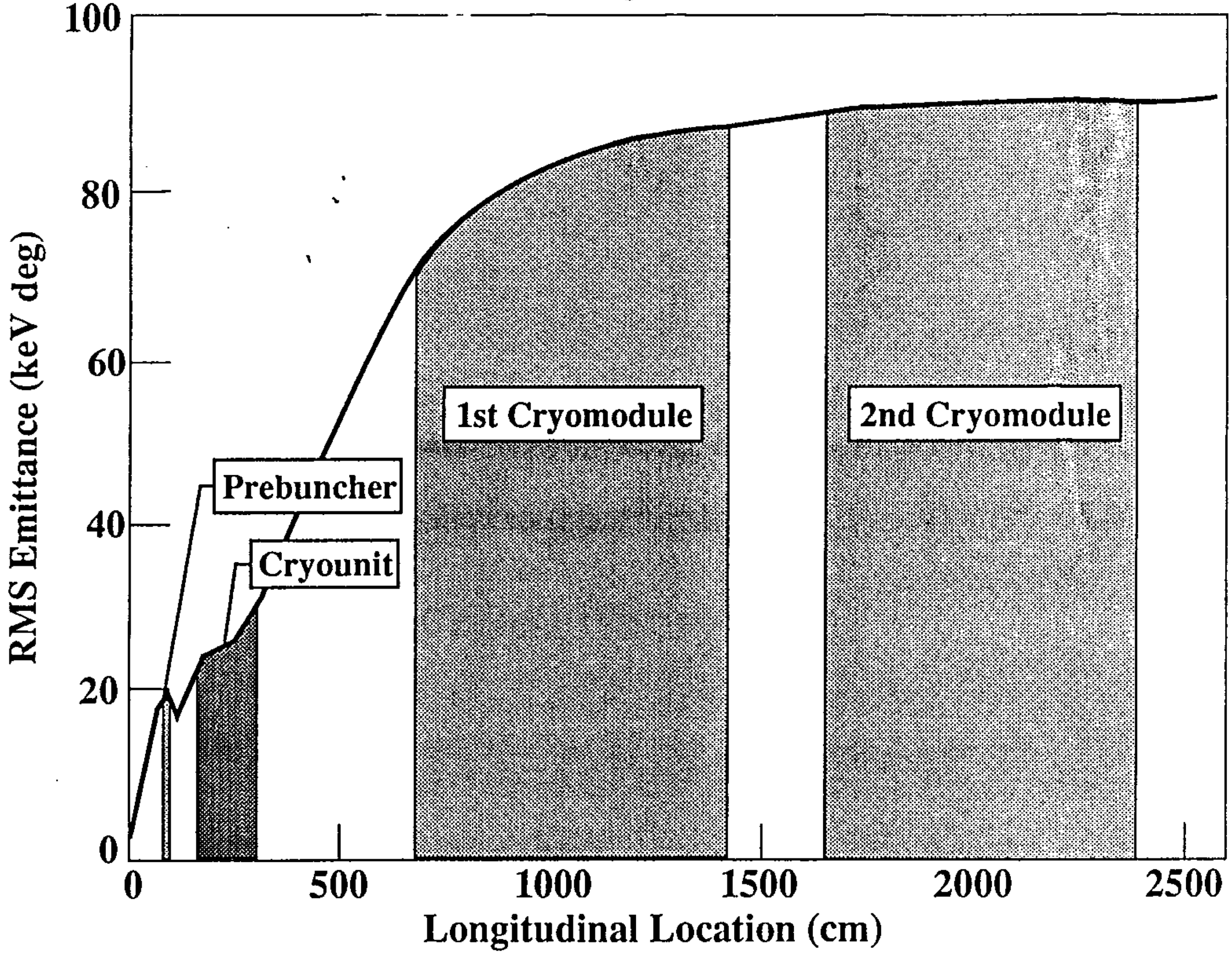


Figure 6



1.20
1.15
1.10
1.05
1.00
0
500
1000
1500
2000
2500
RMS Normalized Emittance (cm mrad)
Longitudinal Location (cm)
Space Charge On
Prebuncher
Cryounit
1st Cryomodule
2nd Cryomodule
Space Charge Off

Figure 7


100
80
60
40
20
0
RMS Emittance (keV deg)
Prebuncher
Cryounit
1st Cryomodule
2nd Cryomodule
0
500
1000
1500
2000
2500
Longitudinal Location (cm)